5. MANAGING UNCERTAINTIES

Introduction

Since much of the contamination at sites occurs in groundwater and subsurface rock and soil, it is difficult to characterize the nature and extent of residual contamination and migration pathways. Similarly, the multiplicity of contaminant-matrix combinations and related factors make it difficult to predict how effective a remedy will be in advance. Furthermore, it is impossible now to determine what all future site uses and potential exposure scenarios are likely to be. Site characterization, design, and implementation efforts can quickly become complex and time consuming if one seeks to remove all unknown or uncertain conditions and parameter values. Therefore, it becomes necessary to manage uncertainty by weighing the costs and impacts of reducing unknowns through data collection now, against the costs of having to implement contingency plans to address potential issues if the unknown conditions prove to be problematic in the future.

The consequences of residual uncertainties can vary greatly. If a response action is sufficiently robust, it may be unaffected by deviations in the site conditions, thus removing the need to narrow the uncertainty surrounding those conditions. In other cases, alternate conditions may prove fatal to a design and necessitate formulation of contingency plans so that a response action need not be halted when and if those conditions are encountered. The optimum balance point between reduction and mitigation of uncertainties will be site-specific and can be identified by reasoned application of uncertainty management concepts.

This chapter discusses the need to determine the significance of unknowns (uncertainties) and describes the two alternatives for managing those uncertainties that are significant to the decisions being made. An uncertainty matrix is introduced as a tool to facilitate evaluation of the optimum management strategy for a site, balancing uncertainty reduction through data collection and uncertainty mitigation through application of robust technologies and contingency plans.

Unknown=Uncertainty=Data Gap Significant Uncertainty=Data Need

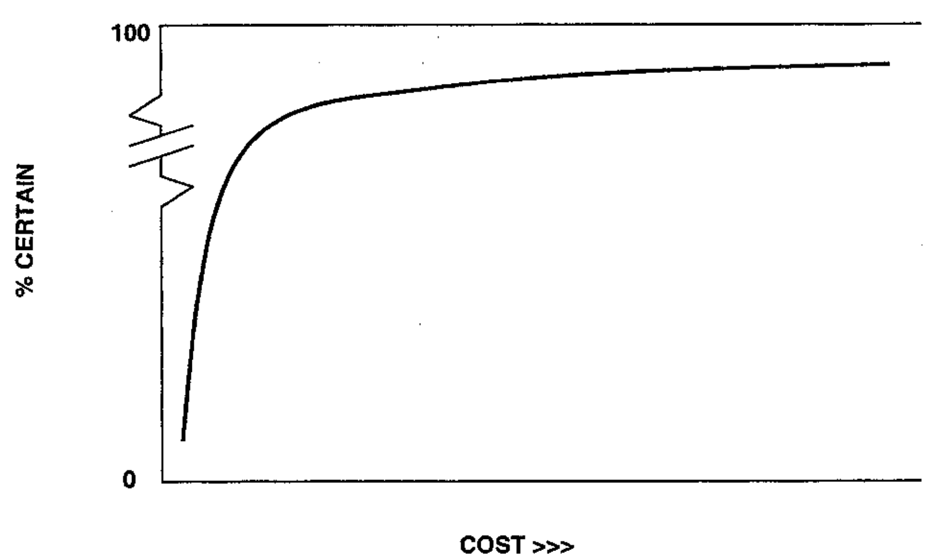
Inevitability of Uncertainty

Principle 4: Uncertainties are inherent in environmental restoration and must always be managed.

Uncertainty management is essential for accelerated progress in site restoration because it helps PMTs make decisions when complete information is not available. Since resolution of all uncertainties or unknown conditions is not possible, the PMT must be able to distinguish between significant and insignificant uncertainties, make decisions when uncertainty exists, and effectively communicate how uncertainties are addressed.

It is important to note that, for decisions based on environmental measurement, no amount of resources can eliminate uncertainty and no management plan can guarantee that some degree of uncertainty does not remain. Figure 5-1 illustrates the relationship between investigative cost and uncertainty reduction. Theoretically, there is no limit to cost. Theoretically and pragmatically, 100 percent certainty cannot be achieved.

Figure 5-1: Data Utility Curve



Historically, it was assumed that uncertainty was resolved once site characterization was complete. If conditions were not well characterized, default values were assigned and presumed to be correct. The probability that assumed values were not correct, and the impact of uncertainties related to technology performance and future site use, were not formally addressed. However, the inevitability of uncertainty is clear in the universal use of monitoring with any remedy that leaves chemical residues in place. If there were absolute certainty in the effectiveness of a proposed remedy, no monitoring would be required. The imposition of monitoring requirements is a clear acknowledgement that uncertainties in technology performance persist.

This Principle focuses on an opposing approach wherein uncertainties are clearly identified and a formal strategy for their management is developed by the PMT. Uncertainties of many types must be understood and managed to generate effective restoration strategies. Page one of the CERCLA guidance for RI/FS says:

> *"A significant challenge . . . is the inherent uncertainties . . . ranging from potential unknowns regarding site hydrogeology and the actual extent of contamination . . . . While these uncertainties foster a natural desire to want to know more, this desire competes with the Superfund program's mandate to perform cleanups within designated schedules. The objective of the RI/FS process is not the unobtainable goal of removing all uncertainty, but rather to gather information sufficient to support an informed risk management decision . . . . As hypotheses are tested and either rejected or confirmed, adjustments or choices as to the appropriate course [of action] are required. These choices . . . involve the balancing of a wide variety of factors and the exercise of best professional judgment."*

Key Concepts in Uncertainty Management

In order to develop an effective uncertainty management strategy, it is important to be able to perform three tasks:

1) Determine the significance of the uncertain parameter and the consequence of assuming an incorrect value;
2) Evaluate tradeoffs between cost of data collection and "decisional benefits" obtained compared to the cost of mitigation through adoption of contingency plans; and
3) Achieve PMT consensus to optimally balance data collection and contingency planning.

These tasks are best performed when the following are understood:

- The impact of uncertainties on project objectives (i.e., knowing whether the PMT can "afford" to be wrong (and how wrong), or whether the PMT must be right). If the value for a parameter is not known, but any probable value will not change the decision being made, the data gap is not a data need and, by definition, the uncertainty is not significant.

- Tradeoffs between the benefits gained from additional information (e.g., ability to use less expensive response) versus the cost (funding and schedule) to obtain it. The tradeoffs illustrate the central concept of determining when uncertainties can be managed in an effective and efficient manner.

- A strategy for managing uncertainty should be defined that will provide the balance between reducing and counteracting uncertainty at the least cost. In some cases, the uncertainty must be reduced to acceptable levels through investigation (e.g., review existing data, site characterization, treatability studies). In other cases, the residual uncertainty is counteracted by contingency planning (If X happens, then do Y).

- The approach to managing uncertainty must be a PMT consensus. The history of a site may make it important to have a wider level of comfort (less uncertainty) than would be acceptable to just the PMT or technical project team staff. The process for establishing acceptable levels of uncertainty may include the general public (e.g., a restoration advisory board).

- Consideration of uncertainty starts in scoping and continues through implementation.

For any given installation, there is a balance of uncertainty reduction and uncertainty mitigation that is optimum with respect to cost, time, or risk objectives. At some sites (e.g., an area with surface soil contaminated by dioxin), strenuous efforts to reduce uncertainty in advance may pay off in a much more efficient cleanup because of the high cost associated with any efforts to remove and destroy this contaminant. At other sites (e.g., a heterogeneous landfill), prior characterization may have little benefit, because of the impracticability of identifying representative samples, and the challenge is to manage uncertainty during remediation. At most installations, both approaches are used to some degree. Optimization means striking the right balance between the two.

Significant Uncertainty

The significance of an uncertainty arises from the degree to which the value of an unknown parameter or condition impacts a decision that must be made. If the same decision will be made regardless of the value, the value has no benefit to that decision and the uncertainty is insignificant. On the other hand, if the range of probable values for an unknown parameter or condition includes those that could change the outcome of the decision, the uncertainty is significant. When addressing decisions as to whether a problem exists, significant uncertainties include contaminant concentrations, the presence of pathways and receptors, and the nature of future site uses. When addressing decisions related to selection of a response, significant uncertainties include those associated with fatal flaws (i.e., ability to meet remedial action objectives) and selection parameters (i.e., characteristics that make one alternative preferable over all others) for the hierarchy of preferred technologies.

For an uncertainty to be significant, there must be the potential for at least two conditions or values, one of which would change the pending decision. This implies that within the range of probable values for any significant uncertainty there lies a decision criterion (threshold value) at which the decision would change. For example, a PMT is considering selecting soil vapor extraction for removal of solvents from contaminated soil and the permeability of the soil is not known. The uncertainty is significant for the remedy selection decision if the range of probable values spans a threshold value of 10-5 cm/sec at which point extraction becomes infeasible.

There are two types of insignificant uncertainties (i.e., do not represent a data need): 1) Those that are insignificant due to the nature of the uncertainty; and 2) Those that are insignificant because the range of probable or likely values falls completely below (or above) the threshold at which a decision would be changed. Insignificant uncertainties for a given problem (i.e., those that do not affect the overall direction of the project) are not necessarily trivial. For example, if a storage area has a capacity of 100,000 cubic yards and a response will only generate between 3,000 and 10,000 cubic yards, the volume of material to be generated is insignificant to the action. However, using up to 10 percent of available capacity for one response may create other installation-wide issues. Therefore, the PMT must review uncertainties in all relevant contexts before dismissing them.

Alternatives for Managing Uncertainty

Uncertainty can be managed through reduction or mitigation. *Reduction* is accomplished by collecting sufficient data to narrow the range of probable values until it no longer spans the relevant threshold for the decision being made. In the example from the preceding section, soil vapor extraction tests could be conducted in hopes that better data would indicate soil permeability was characterized as being greater than or less than 10-5 cm/sec. *Mitigation* is accomplished by making the decision in a way that is insensitive to the uncertainty (e.g., has a higher or lower threshold so that the range of probable parameter values no longer spans the threshold). The latter may be achieved by identifying a contingency that would be invoked if the true value were found to lie on the other side of the threshold than assumed when the decision was made.

The remedy being contemplated can affect both the significance of specific uncertainties and the identity of the optimal means of management. For example, at a landfill where exhumation is being considered, volume to be excavated can be important with respect to capacity of the proposed disposal site. Volume would not be important if capping were contemplated. In the former case, the volume uncertainty is best mitigated by having a contingency plan for dealing with extra volume and proceeding with implementation, since the exact volume can not be known until excavation is complete. (There are numerous examples of extensive characterization efforts underestimating volumes to be excavated because of soil heterogeneities and the cost of sampling on a fine-scale grid.)

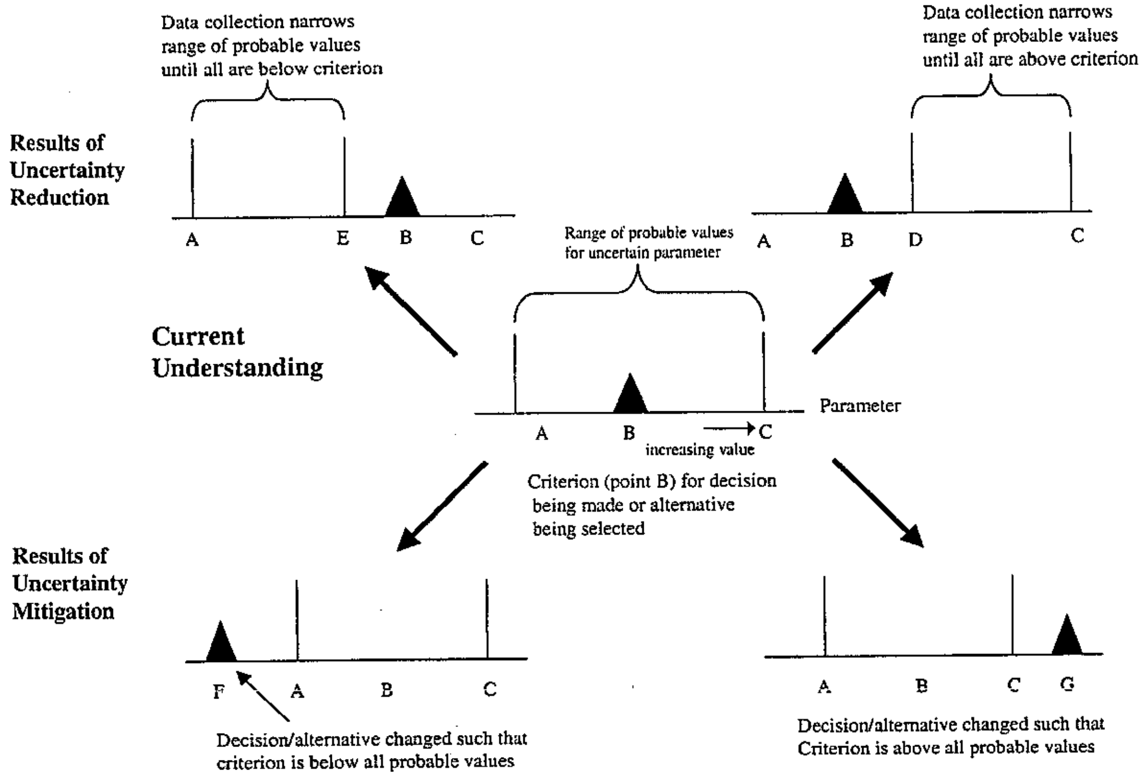
Alternatively, if capping to preclude leaching is contemplated, the presence of waste below the water table is a fatal flaw. Implementation will not lead to discovery of the flaw and will frustrate attempts to mitigate the problem. Therefore, this is an uncertainty that must be reduced. The presence of submerged waste may not be all that significant for the exhumation option unless depths are sufficient to necessitate dewatering or shoring.

Uncertainties must be understood in order to be managed effectively. Organization, documentation, and planning of environmental restoration projects must be performed with the uncertainties and their consequences in mind. There are numerous ways in which the PMT can be "wrong" or uncertain about an installation and its problems. Categorizing uncertainties by source helps to focus on the type of data needed to manage or reduce the uncertainties identified. Sources of uncertainty include site characterization, technology selection, regulatory requirements, and future land use. These sources of uncertainty are interrelated. For example, uncertainties in site characterization lead to uncertainties in whether a technology will work and what regulations apply. Uncertainties in technology performance can lead to uncertainties in regulatory compliance.

Significant uncertainties that must be reduced prior to an action represent data needs. The data may be obtained prior to implementation of a remedy (e.g., site characterization, pilot-scale treatability study), or it may be possible to collect the data during implementation. Significant uncertainties that can be managed effectively are those that can be addressed through a contingency plan. Such contingency plans are included in decision documents, or subsequent design documents.

The approach to managing uncertainty will include both reducing and mitigating uncertainty (Figure 5-2). The challenge is to reach PMT consensus in establishing the balance between the two components.

Figure 5-2: Options for Uncertainty Management



Characterizing Uncertainty

Uncertainty management allows the PMT to change emphasis from assessment to implementation where appropriate (Figure 5-3). Uncertainties can be characterized by the following information:

- Likely or expected condition - this is the assumed value for the unknown parameter or condition given all available data (e.g., permeability is 5x10-4 cm/sec).

- Range of probable values including all reasonable deviations from the expected condition - this is the full range of probable values for the unknown parameter or condition estimated from the available data and any bounding calculations that can be made (e.g., soil size characterization is categorized in literature as having a potential permeability range of 10-3 to 10-6 cm/sec).

- Probability of occurrence - this is a qualitative statement of the likelihood that the assumed value is significantly wrong (e.g., high, medium, or low).

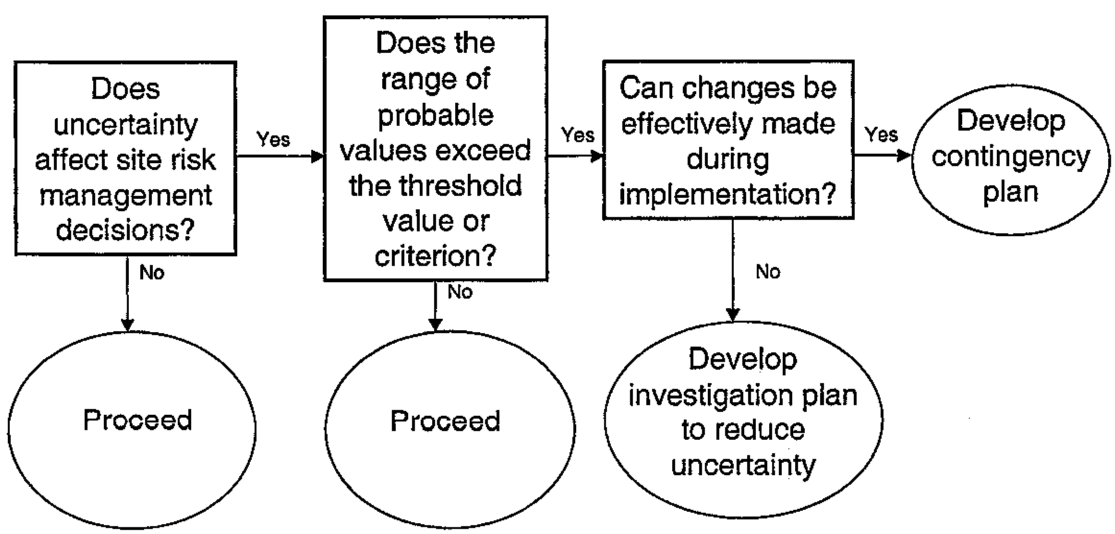
- Time to respond - this is an estimate of how long the PMT would have to correct for a deviation once the true value was observed (e.g., years -- since low permeability would minimize potential impact of soil contamination on ground water, delays in implementation would not add significantly to immediate risk).

- Potential impact on problem response/resolution - this is an indication of how the deviation would impact response effectiveness or attainment of remedial action objectives and should identify any threshold value that may be relevant (e.g., if permeability is less than 10-5 cm/sec, extraction will not be effective and time to cleanup will be extended decades).

- Monitoring plan - this identifies the means by which the uncertain parameter or condition could be monitored during implementation to detect deviations from the assumed value (e.g., measure pressure drop between extraction and observation wells and calculate indicated permeability).

- Contingency plan - this identifies the course of action to be taken if monitoring indicates that a significant deviation does exist (e.g., pneumatic fracturing will be performed throughout the contaminated zone).

Figure 5-3: Uncertainty Management Approach



All factors are assessed to determine how an uncertainty will be managed - either by reducing it or developing a contingency plan. The example uncertainty management matrix provided in Figure 5-4 focuses on uncertainties associated with the implementation of a likely response action, and illustrates how this tool can be used to help organize information needed to classify identified uncertainties into the following categories and document the management strategy:

- Uncertainty insignificant to ultimate objective - probable values do not span decision criteria.
- Uncertainty must be reduced with more data - uncertainty is significant and cannot be mitigated at less cost than that required for data collection to reduce it.
- Uncertainty significant, but can be managed by contingency plan at lower cost than data collection required to reduce it.

Figure 5-4: Categorizing Impact of Uncertainties

Consider a landfill which is to be exhumed to meet regulatory requirements for closure.

Probable Condition	Reasonable Deviation	Probability of Occurrence	Time to Respond	Potential Impact	Monitoring/ Investigation	Contingency Plan
Saturated soil conductivity expected to be 10E(-4) cm/s	Conductivity likely to range from 10E(-2) to 10E(-7) cm/s	High (based on existing hydrogeologic data)	Long	Low - May impact the drainage of rainwater if <10E(-4) cm/s	N/A	Insignificant - No impact on likely response action.
Soil is expected to be stable (i.e., greater than Class C)	Soil may be unstable (i.e., <50% or soil is less stable than Class C)	Low (based on results of previous slump tests)	Short (excavation face may sluff or cave in)	High - Threat to worker safety - Could increase cost or delay schedule	Conduct visual inspections an additional slump tests	Significant - Shore walls - Lay back excavation
Contents are expected to be solid waste only	Hazardous waste may be encoun-tered	Medium (based on process knowledge	Short (to prevent excavation from being delayed)	High - May delay excavation - May increase disposal costs and change handling requirements - May pose worker safety problems	Sample and analyze excavated materials; compare results to regulatory criteria	Significant - Develop contingency plans for excavation, storage, and disposal of hazardous waste; analyze cost impacts to ensure available funding

Uncertainty management is appropriate for both individual projects and larger installation-wide programs. In both cases, it starts with the initial assessment of existing data and the initial construction of the conceptual site model (CSM). With an initial CSM, uncertainty management assists in defining the data needs and/or other strategies for addressing uncertainty with respect to the existence or nature of a problem. Once a problem has been substantiated, its focus is on whether the technology can meet the desired cleanup objectives. The uncertainty management strategy should be addressed formally in the documentation of the investigation results, technology evaluation, and remedy selection. Finally, it is evaluated throughout remedy implementation to determine if any uncertain conditions are realized.

The consideration of uncertainties and their impact does not occur at any one discrete point in time. Rather uncertainties are continually evaluated throughout the investigation, design, and implementation phases. The iterative nature of the feedback is particularly evident during implementation. For instance, the nature of residual uncertainties may influence the type of contract vehicle being considered. Once a contract type is selected, contingencies must be scoped into the statement of work. If contingency costs are too high, an alternate design basis may be appropriate. Ultimately, the alternate design may best be implemented through a different contract vehicle.

Uncertainty management occurs in all phases of environmental restoration. In the pre-decision document phase, the emphasis is on determining the viability of potential risk pathways or other essential elements needed to substantiate the existence of a problem. In the post-decision phase, uncertainty management is used to decide among designs and contingencies that are robust enough to ensure protectiveness in the event that assumed values were in error. During post-construction or closure, the emphasis is placed on conduct of long-term monitoring and interpretation of results to indicate if the remedy is performing in a manner that will meet objectives or if contingency plans must be implemented.

In summary, categorizing uncertainties:

- Forces explicit statements and consensus on uncertainties that may exist.

- Establishes agreed to approaches to manage uncertainties: Lack of explicit recognition of uncertainties, lack of consensus, and lack of planning on how to proceed will create substantial project management and project performance issues.

- Makes explicit the needs for data collection and/or contingency planning: Once problems are defined, data collection, studies, investigations, and analyses should be focused on identifying and planning how to manage uncertainties by balancing the means of reducing or mitigating.

- Helps document how the response will proceed: Uncertainty management strategy needs to be explicitly agreed to among PMT members and communicated with other stakeholders.

- Facilitates closeout by minimizing pursuit of unneeded data.

Not defining and discussing acceptable uncertainty is the source of most differences in opinion. The more explicit the PMT is in what uncertainties exist, what their impacts are, and how they will be addressed, the more likely it is that a consensus can be reached.

Summary

Uncertainty is inherent in environmental restoration. If the uncertain parameter or condition has an impact on a decision that must be made, it is significant and must be addressed specifically in the uncertainty management strategy. Uncertainties can be reduced through data collection or mitigated through use of robust technologies or contingency plans. The selection between the two options should be driven by the cost associated with each and the potential impacts of making a wrong decision. In general, most practitioners default to reduction even though that often involves higher costs. Moreover, many insignificant uncertainties are similarly reduced with no net benefit to the project.

Uncertainty management should be undertaken formally with a documented strategy that clearly outlines the residual uncertainties and the basis for selecting the management technique applied. An uncertainty matrix is a useful means of organizing the required analysis and communicating the resulting strategy.